The Role of Cloud and Fog Water Inputs in the Hydrological Budget of a Tropical Cloud Forest Ecosystem in Costa Rica

Final Report SNF Project 2100-068051.02

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Executive Summary

The scientific goal of this SNF funded project was to **quantify the role of cloud and fog water inputs in the hydrological budget of a tropical cloud forest ecosystem in Costa Rica**. This goal was successfully achieved, although the results did not actually confirm previous estimates of fog water inputs to cloud forests. While literature estimates were suggesting that 28% of the total water input to a Costa Rican cloud forest could be fog water deposition, our sophisticated direct flux measurements of fog droplet deposition to the forest canopy actually suggest that this share is **almost an order of magnitude lower than previously believed**, namely 3.2% during the period of measurement in early 2003.

One explanation could be that our measurements actually measured the vertical – or more precisely the surface-normal – flux of fog droplets to the canopy, while fog water deposition in reality in such diverse forests could be mainly due to prominent tall trees and uneven height of the canopy. However, a careful analysis of conventional precipitation measurements that has been carried out by now indicates that the uncertainty of rain gauge measurements is large enough in this tropical environment with torrental rains and strong rain-driven precipitation, to account for the discrepancy between water input (precipitation and fog) and output (throughfall, stemflow and evaporation of intercepted water from the vegetation canopy) that was found in the overall hydrological budget. **Measured rainfall from standard rain gauges had to be corrected by a factor 1.255** to account for the known effets of wind speed, wind direction in relation to mountain slope exposition and slope aspect angle.

Concentrations of inorganic ions in fog water were enriched by a factor 1 to 7 depending on species, which suggests that the crucial role of fog in cloud forest ecosystems might be either related to the ion inputs which have a much longer contact time in the canopy compared to rain, or to prevent dessication during rainless periods where the benefit of not evaporating large amounts of water might be superior to the minor input of fog water by droplet deposition. Stable isotope concentrations ($\delta\,^{2}$H and $\delta\,^{18}$O) which were not yet available at the time of this writing might provide further insight into the processes that make fog so important for cloud forest ecosystems in tropical mountain areas.

Contents

Chapter 1

Introduction

1.1 The FIESTA (Fog Interception for the Enhancement of Streamflows in Tropical Areas) project

Declining streamflows in Central America constitute a major problem for rural and urban water supplies and potentially hamper agricultural production and hydropower generation during the dry season. The causes may include the clearing of montane cloud forest (mostly for pasture) and regional climatic change induced by large-scale deforestation in the lowlands. This project aims to quantify the impact of cloud forest conversion to pasture on streamflow in the Tilarán Range of northern Costa Rica using hydrological process research and modelling. A measuring protocol will be developed for use at other locations in the region as well as a physically-based catchment-scale hydrological model (FIESTA) to assess the basic hydrological and economic impacts of (cloud) forest conversion. The latter is a *conditio sine qua non* for designing realistic 'payment for environmental services' schemes compensating uplanders for sustainable land stewardship.

The project's direct purpose is the quantification of the much debated change in streamflow that is to be expected after converting montane cloud forest to pasture, initially under the climatic conditions prevailing in northern Costa Rica and at the micro- to meso-catchment scale (< 100 km^2). Adopting a process-based approach, the dominant factors governing vegetation water use and streamflow is evaluated in a spatially explicit manner. The physically-based approach allows judicious upscaling of plot-scale measurements to the meso-scale at which operational hydrology is often executed. The process-based model to be developed by the project may be used elsewhere (both within and outside Central America) for the prediction of the hydrological and economic impacts of montane forest conversion. Arguably, such predictions could provide a more realistic base for the design of payment schemes for environmental services in which downstream beneficiaries compensate upland farmers/forest managers for sustainable land and forest stewardship.

The recent publicity wave around the crashes in frog and lizard populations in the leeward cloud forest at Monteverde is attributed to climate change (Pounds et al. 1999). Additionally the changes in cloud formation patterns above the northern Atlantic coastal plain of Costa Rica following widespread lowland deforestation (Lawton et al. 2001) constitutes further evidence of the need for specific research aiming at the understanding of the complex functioning of the vulnerable cloud forest ecosystems. By concentrating such work in the same area where most of the climatic change research is already taking place, chances of successfully separating land-cover and climatic effects on streamflow will be maximised (Bruijnzeel 2001).

1.2 The contribution of the present SNF project

The goal of this finished SNF project was **to quantify directly cloud and fog water inputs with state-of-the-art scientific equipment in order to assess their role in the hydrological budget of a tropical cloud forest ecosystem in Costa Rica.** In addition to this main goal the ionic concentrations and the isotopic signature (not shown in this report) in the different waters (fog water, rain water, throughfall and stemflow samples) were analysed in order to use different approaches of calculating the hydrological budget by indirect methods. This project was designed as a one-year add-on to the international "Impacts of Cloud Forest Conversion" project funded by the UK and guided by Dr. L. A. Bruijnzeel (Vrije Universiteit Amsterdam) in order to participate during their field campaign in Costa Rica. The deliverables of this SNF project were the eddy covariance flux measurements of cloud or fog liquid water which are a significant component in the hydrological budget of tropical montane cloud forests (i.e., indirect estimates quantify this input as 28% of concurrent precipitation input; Bruijnzeel 2001).

The aspect of direct measurement of cloud and fog water deposition to a tropical (cloud) forest was the focus of this SNF project. With the exception of the measurements carried out in Puerto Rico (Luquillo Experimental Forest site) during summer 2002 by Reto Burkard (PostDoc during this project) comparable measurements have not been carried out before in the tropical region.

Chapter 2

Experimental

2.1 Site

Hydrological and micrometeorological measurements were performed within a small catchment within the Cao Negro drainage basin, located 7 km NE of the town of Santa Helena (San Gerardo farm; national grid coordinates: $^{2}58$ – $^{2}62$ and $^{4}48$ – $^{4}5$, Tilarán topo sheet). Most of the measurements described in this report were carried out on a 24 m heigh meteorological tower above the forest canopy (see Figure 2.1).

Figure 2.1: Meteorological tower (24 m height) with our measurement equipment on top.

2.2 Methods for measuring fog water deposition

The vertical flux of fog droplets in a forest canopy is governed by two main processes. The most important is the diffusion by turbulent movements through the atmosphere followed by impaction of the droplets on vegetation elements. The second process is the gravitational settling. Both deposition processes are largely determined by the size distribution of the fog droplets. The turbulent part of the total liquid water flux can be measured directly by employing the eddy covariance method where the gravitational settling can be calculated by the droplet size distribution during fog. The gravitational flux was determined using the Stokes settling velocity as described in Beswick et al. (1991). The turbulent flux was calculated by means of the eddy covariance method. This method is based on the assumptions that turbulent fluxes in the atmosphere are driven by the short-term fluctuations of the wind vector, i.e., the turbulence. Gases, small-sized particles and water droplets contained in an air parcel follow the turbulent motions of the air. The turbulent flux in the vertical direction can therefore be expressed by the covariance of vertical wind speed w and liquid water content (LWC). Further details on the measuring method of liquid water fluxes are given in Burkard et al. (2002, 2003). In summary, the total flux of fog water is the sum of the turbulent liquid water flux plus the gravitational liquid water flux.

2.3 Instrumentation

Units of the Eddy Covariance Set-up

The liquid water fluxes were measured with a three-dimensional ultrasonic anemometer (model 1199 HSE with a builtin inclinometer, Gill Ltd., Solent, UK) and an active high-speed FM-100 cloud particle spectrometer (Droplet Measurement Technologies, Inc., Boulder, CO, USA). Its principle of operation is described in detail in Burkard et al. (2002). Fog droplets within the diameter range 2 and 50 mm were categorized into 40 size bins. The anemometer and the FM-100 were operated at a sampling rate of 12.5 Hz in order to resolve most of the frequency spectrum of turbulent motion. The fog water flux equipment was connected via digital serial data lines (RS-422) to a laptop computer. The data were then transferred to a SUN workstation for evaluating and processing by the in-house software CONVERTALL version 11.08. The main functions of this software are the calculation and averaging of the liquid water fluxes from the raw eddy covariance data over half hour periods. A detailed description of the basic concepts of this software can be found in Eugster (1994).

Fog water Sampling

To investigate the occult deposition of nitrogen and other trace elements it is necessary to determine the chemical composition of the fog water. Therefore, a modified Caltech Active Strand Cloudwater Collector (CASCC; for details see Demoz et al. 1996; Daube et al. 1987) was mounted at a height of 24 m a.g.l.

Air containing fog droplets is drawn by a fan through a conduit of the CASCC where the droplets are collected by impaction on six rows of Teflon strands. The fog water is then drawn down to the lower ends of the strands, where they drop in a teflon channel before they were diverted in a sample bottle for collection. To avoid the sampling of rain water, the intake of the CASCC was covered with a rain protection shield.

During the field campaign in Costa Rica, the CASCC was triggered by the visibility measurements of a present weather detector. Whenever the visibility was below 500 m the fog water collector is switched on, at visibility values higher than 500 m it was switched off.

Additionally, two CASCC owned by the group of Jeff Collett (Colorado State University) were continously running at 16 m a.g.l (in the vegetation canopy) and at 20 m a.g.l (at the top of the vegetation canopy). This collectors were installed to sample the fog water at different heights for providing us a profile of the chemical compounds and the isotopic signature in the fog water depending on

- the measuring height above ground, and
- on the position within the canopy or above the forest canopy, respectively.

Ancillary Meteorological Measurements done by the authors of this study

Meteorological measurements were performed by employing a data logger (Campbell Scientific, Inc. model CR10X), which stored average data (measuring interval was 10 sec.) every 10 minutes: Global radiation, reflected short-wave radiation, incoming and outgoing long-wave radiation. These measurements were done using a Kipp & Zonen CNR1 net radiometer. The photosynthetic active radiation (PAR) was measured using a Skye SKP215 PAR quantum sensor. The radiation measurements were performed at a height of 24 m a.g.l. Air temperature and relative humidity were measured by using a Rotronic Hygrometer MP100A (with radiation protection shield; 2 m a.g.l.). Air pressure was measured using a Vaisala PTB101B analog barometer. The wind speed (A100R Switching Anemometer, Vector Instruments, UK) and the wind direction (W200P Potentiometer Windvane, Vector Instruments, UK) were measured at a height of 26 m a.g.l. To detect the presence or absence and the density of fog, and to control the fog water collector, a present weather detector (PWD11 manufactured by Vaisala, FI) which measures the visibility, the rainfall amount and the rainfall intensity, was mounted at 24 m height of the tower.

To compare both the ionic concentration and isotopic signature of fog water and rain water as well as wet and occult deposition, rain water was also collected. Rain water was sampled by a wet-only sampler with a device for collecting automatically successive rain water samples which was developed at the University of Bern. A reflective aluminium cover minimizes direct heating by solar radiation. The rain droplet detection sensor consists of an array of conductive laminae over a camshaft which removes raindroplets from the gaps between the laminae by vibration. As soon as this sensor registers a rain event, it opens the lid until 7 minutes after the last rain drop has been fallen. A detailed description can be found in Eugster (1999).

Ancillary Measurements performed by the FIESTA core team

During the entire FIESTA project many different (micro-) meteorological measurements were performed on different locations. Especially at the tower site were a lot of additional profile data were available thanks to wind speed, wind direction, temperature, humidity, visibility and radiation measurements. In order to quantify and asses the role of the different water inputs in the hydrological budget, rainfall and fog water amounts were measured at different heights by employing a tipping bucket rain gauge, a standard rain gauge (both connected to a data logger by Campbell Scientific), different types of totalizing rainbuckets and fog water sampling systems (Juvik Fog Gauge, Standard Wireharp Fog Water Sampler by Schemenauer, cf. Bruijnzeel 2001). In a distance of several hundred meters away from the tower site throughfall and stemflow measurements were performed:

Throughfall was measured by two different methods in order to have representative measurements: By the roving sampling technique where 60 totalizing rainbuckets were placed by randomly selecting a subset of all pre-defined possible sampling points along a transect line to obtain throughfall water samples. The course of the transect line was chosen with the intent to take the variation in the vegetation cover into account as much as possible. Each sampling period, the throughfall volume of every single rainbucket was measured by a measuring cylinder. The values were then averaged to the representative throughfall amount for a specific sampling interval. The other approach was to measure the occurrence and the intensity of the throughfall continuously by using fixed installed steel gutters which were equipped with a tipping bucket and a logger system. Studies by Lloyd and Marques (1988) and Holwerda et al. (2003) showed that the amounts of throughfall measured by random relocation of totalizers is more representative for the spatial variability of the forest canopy than when throughfall is measured by fixed position totalizers.

As an important term in the water mass balance of a forest ecosystem, stemflow was measured at 30 representative trees (e.g., diameter of the stem and canopy, height etc.). The water was sampled by a polypropylene funnel, which was wrapped around the base of the stem. The sampled water was then drained in bottles, which were regularly cleaned with deionized water. The volume of the collected stemflow water was determined manually by a measuring cylinder.

For further information on these additional measurements we refer directly to the project proposal of the international "Impacts of Cloud Forest Conversion" project funded by the UK and guided by Dr. L. A. Bruijnzeel and to the work done by Bruijnzeel (2001), the latter giving an overview of the different techniques to quantify the different water inputs involved in the hydrological budget.

2.3.1 Chemical Analysis

Fog, rain, stemflow, and throughfall water samples were stored in precleaned polyethylene bottles in the freezer until they were sent in cooling boxes in order to avoid evaporational processes during the transport, to the Institute of Geography (GIUB) in Bern, Switzerland, for chemical analysis. The chemical analysis included the measurements of the pH, specific electrical conductivity, and the concentrations of major ions (F^-, Cl^-, NO_2^-, PO_4^{3-}, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}). The pH was measured using an electrode (Single Pore pH Electrodes, manufactured by Hamilton, CH) with automatic temperature correction. The electrical conductivity was determined by an electrode (Standard conductivity cell, TetraCon manufactured by WTW, D). After filtration (0.45 μm nylon filter) the fog and rain water samples were analyzed by ion chromatography using a Dionex DX120. During the field campaign, several blank samples were collected in order to estimate the contamination of ions due to the collector or sample handling. No significant contamination of ions was observed, neither before cleaning the fog water collector (after a regular fog sample or a period without fog) nor after cleaning the CASCC. In order to keep the CASCC as clean as possible, the running collector was sprayed with deionized water after collecting a sample (usually twice a day). The CASCC was switched back to normal operation 10 to 30 minutes later in order to prevent the collection of fog water from dilution by the deionized water. The collected water samples for chemical analysis were filtered through a 0.45 μm nylon filter to remove solid particulate matter.

Chapter 3

Results and Discussion

3.1 Meteorological conditions during the campaign

Figure 3.1 gives an overview of the meteorological conditions during the entire campaign. As mentioned in the caption of Figure 3.1, the entire setup was switched off in the period from day 87 to 90 because of stormy weather conditions without fog. The mean temperature was 17.7 degrees Celsius with a maximum value of 23.3 and a minimum of 13.0 degrees Celsius. Except for the end of the stormy weather period the median windspeed shows low variation. The mean windspeed during the entire campaign was 2.6 m s^{-1} and a median value of 2.3 m s^{-1}, respectively. The lower panel in Figure 3.1 shows the temporal variation of the median visibility in meters which will be further used as a measure for the occurrence and frequency of fog at our field site. Even if daily median values are taken into consideration, which are rather robust in respect to extrem low visibilities, it is obvious that days with dense fog during 50% of the time of the day are quite rare.

During 56% of the time with windspeed $>$1 m s^{-1} the winddirection was from northwest to northeast (337.5° to 67.5°), where the sector from southeast to south (112.5° to 202.5°) represents a second maximum. During foggy weather conditions (Figure 3.3) the dominance of the northerly winds is even more pronounced with an obvious increase of the low windspeeds ($<$1 m s^{-1}) during which the winddirections have been measured with a low accurracy due to the design of the cup anemometers.

3.1.1 Fog

The entire campaign was lasting 2013.5 hours. During this time the fog water flux equipment was running 83% of the time (1677 hours), during the remaining hours the equipment was switched off because there was no fog. This stopping of the equipment was introduced during the first few weeks with a weak occurrence of fog at our field site to save some gasoline (and money). The characterization of fog at the field site was done by employing the visibility measurements, which are available during 97% of the time when the system was running. According to the location (exposed on the Atlantic side of the

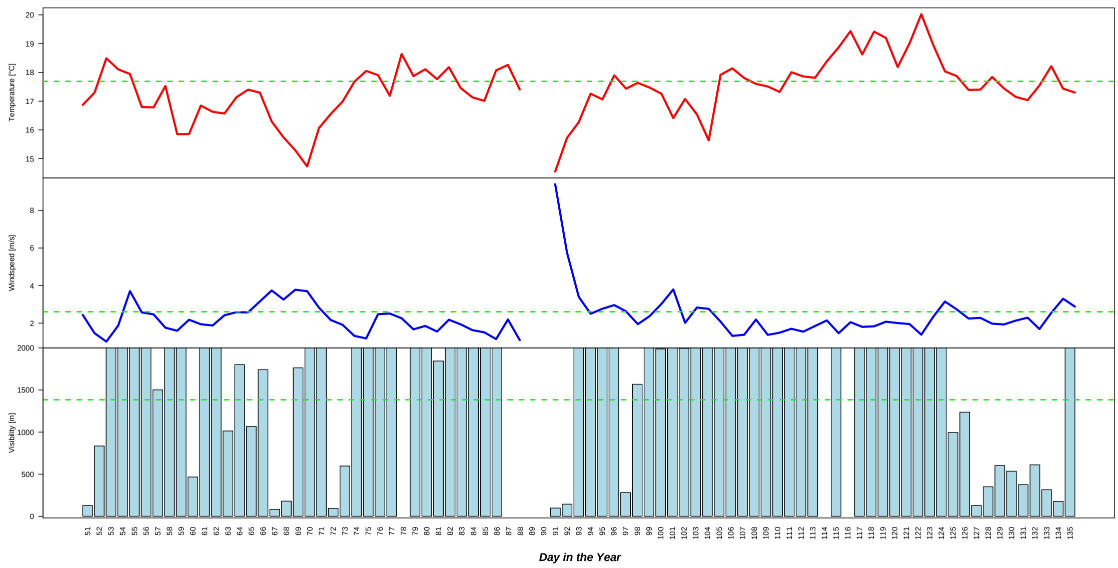


Figure 3.1: Meteorological conditions during the entire field campaign in Costa Rica. Daily median temperature (upper panel), median daily windspeed and median daily visibility in the lower panel. The dashed green lines represent the mean value of the shown parameter during the entire campaign. During the four days (Day 87-90), all the devices were switched off due to lack of fog.

continental divide), fog was formed by clouds advected mostly with easterly winds. During westerly winds from the Pacific, the field site was in the leeward of the Continental Divide and therefore no fog was detected. By definition, fog is a cloud form at the surface of the earth consisting of a multitude of minute water droplets suspended in the atmosphere with a visibility below 1000 m. Only about 26% of the entire field campaign in Costa Rica, fog was detected by the PWD11 (Table 3.1). Clear conditions without fog, indicated by a visibility of 2000 m, occurring for 59.8% of the entire campaign. There exists some uncertainty concerning theses percentages because of the lack of visibility data (see above).

3.2 Data

3.2.1 Precipitation Measurements

Precipitation was measured by different devices: Vertical rainfall was measured by two manual gauges which were emptied once a day, and by an automatic gauge, measuring tips of 2 ml. Furthermore, horizontal precipitation, i.e. fog and horizontal rainfall, was measured by a self constructed, rotating collector with a vertical orifice (called UFO) and by a passive, Juvik-type fog sampler. This sampler was provided with two tipping bucket systems: One measured horizontal precipitation, i.e. precipitation catched by the vertical surface of the cylinder, and the other one measured vertical precipitation, i.e. precipitation falling into a

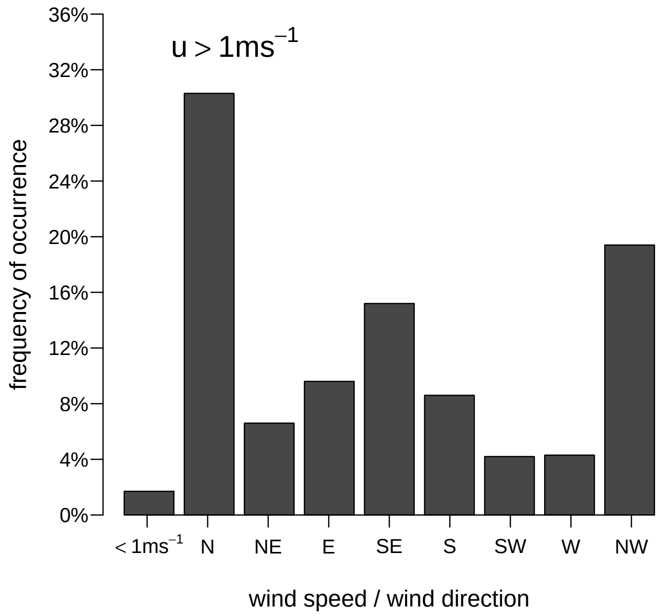


Figure 3.2: Frequency of occurrence of windspeed >1 m s^{-1} with respect to wind direction during the entire campaign. The winddirections during low windspeeds <1 m s^{-1} were not taken into consideration.

funnel which was placed at the top of the cylinder. At the same time the funnel acted as a cap to prevent vertical rain from falling into the tipping bucket system for horizontal rain. Table 3.2 summarizes the rainfall amounts measured by different measurement devices for a 65 days lasting comparison experiment.

There is a difference between the amount measured by the manual and the automatic raingauge. The values of the manual gauge could be underestimated because of evaporation losses and spilling of water while measuring. Because of the higher temporal resolution of the automatic gauge, the following calculations are based on these data.

3.2.2 Throughfall Measurements

Throughfall measurements were carried out once a day. Total amount of throughfall measured in the period between day 68 and 133 was 521.6 mm.

3.2.3 Stemflow Measurements

Stemflow data are available from day 93 onwards. Total amount from day 93 until day 133 is 11016.3 ml. To convert these values to mm, the projected crown area is needed (Marin

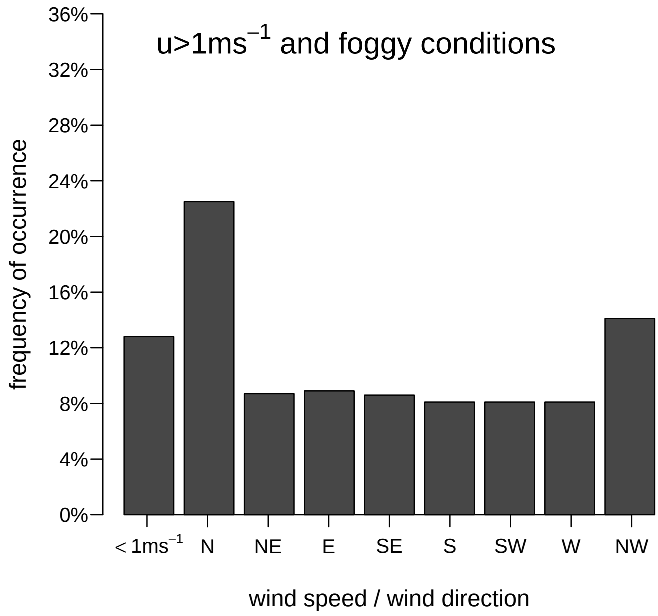


Figure 3.3: Frequency of occurrence of windspeed >1 m s^{-1} with respect to wind direction during foggy weather conditions. The winddirections during low windspeeds <1 m s^{-1} were not taken into consideration.

et al. 2000). Because this value is not yet estimated, the conversion can not be done and a comparison is not possible yet. Nevertheless to be able to solve the water balance, an experience value of 2% of net precipitation, in this case 10.4 mm, is taken (Marin et al. 2000).

3.2.4 Liquid water fluxes

The fog water flux equipment was running 1677 hours, which is more than 83% of the time of the entire field experiment. During the remaining time the devices were switched off due to the lack of occurrence of fog or due to technical maintenances, which were always performed during clear weather conditions. Due to the fact, that the original sonic anemometer belonging to our fog water flux equipment was broken during the transportation to Costa Rica, we were forced to measure with an older device of the same type. The only difference was, that this older device has not been upgraded by GILL Ltd. with the newest release of the internal software, which should improve the functioning of the sonic anemometer during heavy rain conditions (as they can occur in the tropics during strong convective weather situations). Due to the lack of this upgrade – as far as we analyzed our measurement campaign – we had several problems such as short data interupts during stormy weather conditions (low cloud base, heavy rain, high windspeeds), which could not

Table 3.1: Characteristics of fog at our field site in Costa Rica: Duration of foggy conditions, liquid water content (LWC), liquid water flux (LWF), and Volume weighted Mean Droplet Diameter (VMD). The Characterization is based on the visibility measurements.

Visibility [m]	Duration [h]	Percentage for total field campaign [%]	LWC [mg m^{-3}]	LWF [mg m^{-2} s^{-1}]	VMD [μm]
$<$ 100 m	206.0	10.5	270.1	-18.22	12.3
100–250 m	154.0	7.8	196.9	-10.86	11.5
251–500 m	67.5	3.4	102.9	-5.23	9.9
501–1000 m	94.5	4.8	65.7	-1.86	9.0
1001–2000 m	238.5	12.1	12.5	-0.54	7.0
no fog	1203.5	61.3	0.0	0.00	3.8

Table 3.2: Rainfall amounts measured by different devices for a period of 65 days (6 March 2003 – 13 May 2003).

Device	measurement height [m]	rainfall amount [mm]
precipitation manual gauge	24	396.8
precipitation automatic gauge	22	406.3
horizontal precipitation Juvik	22	793.9
horizontal precipitation UFO	24	541.7

be fixed during the campaign. Finally, we missed about 8% (132 hours) of the fog water flux data, due to the use of the older sonic anemometer. Because the weather conditions during these periods were often foggy (low cloud base), we reconstructed the missing data on the basis of the 1-, 5- and 10-minutes averages. Half-hour fog water flux data were calculated by merging these short-time averages. The same way of calculating half-hour fog water flux averages out of short-time data was also performed during periods when the sonic anemometer was running properly. The comparison of the reconstructed and the original flux data did not reveal any major differences. Additionally, several statistical approaches to test the quality of the reconstructed fog water fluxes confirmed the suitability of our approach. Therefore, we used for the further analyses of the fog water deposition in this study the combination of the original and reconstructed flux data. For the period when the sonic anemomenter was running properly the following first-order quality check was performed: the two time series of the FM-100 and of the sonic anemometer were averaged over 1-minute periods. The distributions of these averages did not show any indications for bad data quality such as outliers. Moreover, spectral analysis of wind (u, v, and w) and the FM-100 (LWC) data showed very good agreement with the theoretical spectra by Kaimal et al. (1972) in the high-frequency range, indicating high quality of the wind and FM-100 measurements during the whole field campaign.

During the entire period the total water input by fog water deposition was 26.9 mm, which is the sum of the turbulent (23.6 mm) and the gravitational fog water input (3.3 mm; that is 12% of the total input). For the analysis of the water balance a period during which the most important data (rainfall, througfall, fog water) are available without any interruption were selected (see Section 3.3.1): Between 6 March 2003 and 13 May 2003 the total fog water input (turbulent and gravitational fluxes) was quantified to be 16.6 mm.

3.3 Deposition

3.3.1 Water balance

The water mass balance was used in several studies to estimate fog water inputs (Asbury et al. 1994; Bruijnzeel 2001). The aim of the FIESTA project is to model the impact of deforestation on the waterbudget. The knowledge of the correct water input to the ecosystem - by fog and rain - is essential. Hence the water balance was applied to control whether the water input to the forest was measured correctly. Following formula was applied:

$$P + F = TF + SF + \Delta CS + E_i \ , \tag{3.1}$$

where P is the deposition of rain, F the fog water deposition caused by turbulence and gravitational settling, TF is throughfall, SF is stemflow and ΔCS is the change in canopy storage. E_i is the evaporation from a wet canopy, calculated with the Penman-Monteith equation using data from thermocouples, net radiation, and windspeed. It was assumed that the canopy was wet when there was a signal either from a verical or a horizontal raingauge. In this campaign, the values for a 65 days period, between day 68 and 133, are: Precipitation: 406.3 mm, Fog: 16.6 mm, TF: 521.6, SF (2% of TF): 10.4 mm, E_i: 17.1 mm. ΔCS was neglected. At a first try, the balance does not come out even: the unexplained amount is 126.2 mm. In this study, a sophisticated set-up was used to measure fog water fluxes directly above the cloud forest canopy. For this reason, we expect the fog water inputs to be correct. The deviation from the balance is more likely to be generated by incorrect rainfall measurements. There were many rain events observed with small droplet sizes and high windspeeds, generating horizontal rain. Under these conditions, an underestimation of rainfall amounts is probable (Sharon 1980). On account of this, we tried to correct the rain amounts in order to close the water budget.

3.3.2 Correction of Precipitation Measurements

Sharon (1980) described the influences of rain angle, storm direction, slope inclination, and aspect of slope on the difference between conventionally measured and effective hydrological rainfall. It was found that on a windward facing slope hydrological rainfall can exceed conventional gauge measurements by more than 100%, depending on slope and rainfall inclination. To correct the rainfall measurements of this campaign, the following formula was used (Sharon 1980):

$$P_a = P_0 \left[1 + \tan(a) \cdot \tan(b) \cdot \cos(z_a - z_b)\right] \tag{3.2}$$

where P_a is the effective hydrological rainfall, P_0 the conventionally measured, a the angle of the slope, b the rainfall inclination, z_a the aspect of the slope and z_b the rain direction. The rain direction was given by the wind direction and the angle of rainfall was calculated as follows (Herwitz and Slye 1995):

$$\tan(b) = W/U_v \ , \tag{3.3}$$

where b is the angle of rainfall in degrees from the vertical, W is the horizontal wind speed (m s^{-1}) and U_v is the terminal fall velocity (m s^{-1}). Terminal fall velocity was calculated after Herwitz and Slye (1995):

$$U_v = 3.378 \cdot \ln(D) + 4.213 \ , \tag{3.4}$$

where D is the raindrop diameter (mm). Raindrop diameter was computed on the basis of rainfall intensity (Herwitz and Slye 1995):

$$D = 2.23 \cdot (0.03937\, P)^{0.102} \ , \tag{3.5}$$

where P is the rainfall intensity (mm h^{-1}). Rainfall angles for the period between day 68 and 133 were between 1.43 and 66.27 degrees from the vertical, with a mean of 31.30 degrees. Assuming a slope inclination of 30 degrees and a slope aspect of 20 degrees from north, the corrected rainfall amount for the period between day 68 and 133 is 510.1 mm. This is 25.5% more than the conventionally measured amount. The largest corrections are made for events with high windspeeds (Figure 3.4).

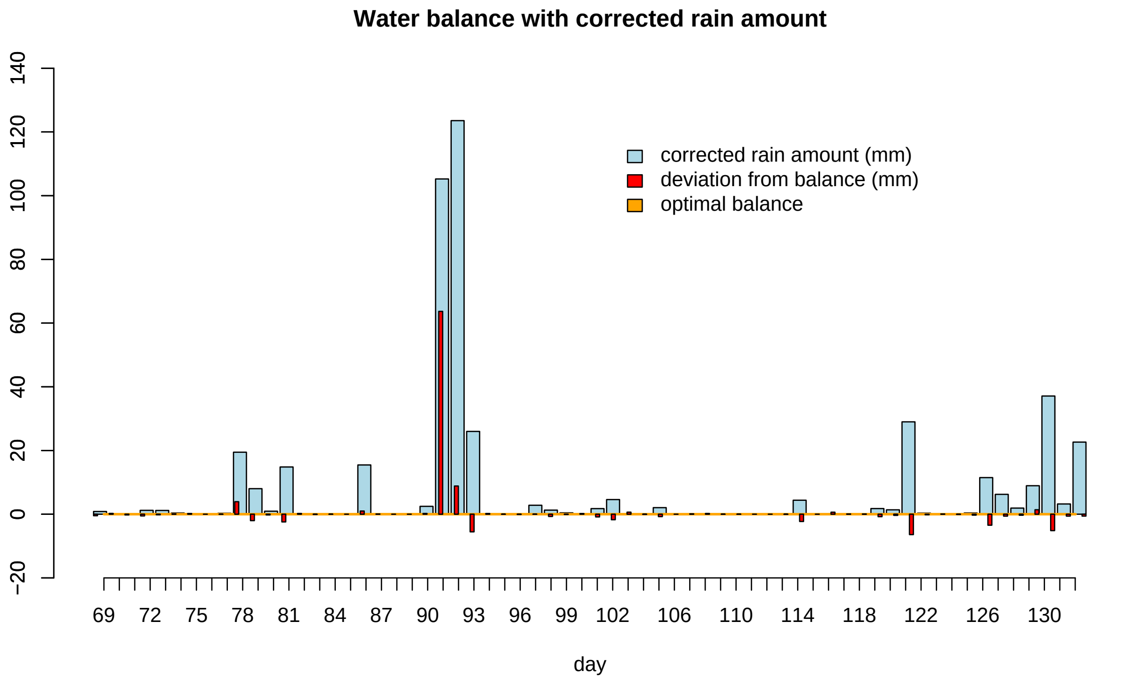
3.3.3 Water Balance with Corrected Rainfall Amounts

With the corrected amount of rainfall, the water balance (entire water amount during the time period on which the correction was applied) looks as follows:

$$510.1_P + 16.61_F < 521.56_{TF} + 10.42_{SF} + 17.09_{E_i} \tag{3.6}$$

The missing amount of water is 22.36 mm. The temporal distribution of the deviation shows that there is still a discrepancy from the optimal balance (see Figure 3.4).

Apparently, the largest deviation originates during the event between day 90 and 94. This event excluded, the balance is even negative, i.e. there was too much rainfall or, more likely, the water was intercepted by epiphytes and evaporated before reaching the ground; it was assumed that ΔCS can be neglected, but if there is a dry up of the canopy, smaller throughfall than rain amounts could be possible. Another possibility is an error created by the measuring setup: throughfall was measured at the opposite slope with an aspect of 340 degrees from north. Arazi et al. (1997) state in their study that small scale topographical inhomogeneities substantially influence the rainfall distribution. Therefore,



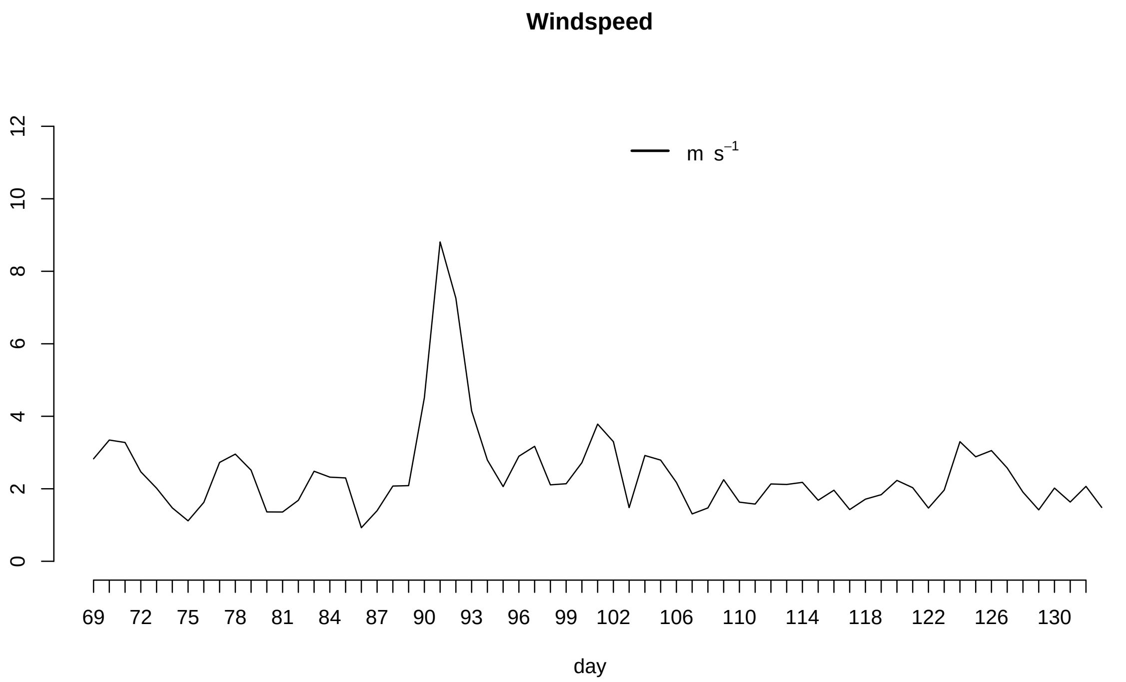


Figure 3.4: Corrected daily rainfall amounts after the application of Sharon' modell (upper graph) and their deviation from the closed water balance. Lower panel: daily mean windspeed.

an uneven rainfall distribution in the catchment could be an explanation for the smaller rain amounts in the area where throughfall was measured. But still, there is an error in the water balance during event of days 90–94. Is the correction of the rain amount appropriate for events with wind speeds above 10 m s^{-1}? Was the rain angle calculated wrongly? With a rain angle of 70 instead of 60 degrees the correction of the rain amount would yield a rain amount appropriate to the throughfall amount. Or was the rain amount underestimated as a result of the tipping bucket system, which is less accurate in case of high rainfall intensities? Another possibility is a malfunctioning of the measurement setup because of the storm event.

3.4 Chemical Composition

The quality of the data was examined by considering the ion balances of the chemical samples and comparing the measured electrical conductivity with the calculated electrical conductivity. For all fog water and rain water samples the ion balances show a good agreement between the sum of anions and the sum of cations (not shown). Table 3.3 shows the volume weighted mean solute concentrations in fog water (F; samples from the top of the tower) and rain water (P; rain water samples from the manual rain gauge) of the most relevant ions, the mean pH and the mean conductivity (Lf in μS) as a measure of total ion loading of a water sample. Lf was very low with an average of 62.42 μS for fog water and 16.28 μS for rain water. Comparisons with previous studies performed by the authors during the FINIMSAS project (Fog Interception and Nutrient inputs to Montane-Subalpine Areas in Switzerland; funded by the Swiss National Foundation 1999–2003), revealed, that the ion loading of the fog water and rain water was extremely low. The ionic composition was dominated by sodium, chlorid and sulphate. This composition could be partly explained by the proximity of the site to the Pacific Ocean. However the Pacific being on the leeward side, urge for further investigation. Some possible explanations are:

- The long-distance transport of the marine ions with the trade winds from the Carribean Sea,
- the intensive volcanic activity of the Arenal, in short distance from the site (about 25 km) at the direction of the prevailing winds.

Table 3.3 shows that the ionic concentrations in rain water sampled in the Costa Rican cloud forest are comparable to the results of studies in central Europe during the FINIMSAS project (Thalmann et al. 2002; Burkard et al. 2003). A huge discrepancy between the studies in Europe and our results exists regarding the ionic concentration in fog water: the fog water ionic concentrations in central Europe are 4 to 10 times higher than in Costa Rica. Good agreement regarding ionic concentrations in fog water and rain water was found with Burkard (2003) carried out at another tropical site (Puerto Rico).

Table 3.3: Volume-weighted mean solute concentrations [μeq l^{-1}], pH and conductivity (Lf) in fog water (F) and rain (P) in comparison to Burkard (2003) for Puerto Rico, summer 2002. The ratios show the accumulation of ions in fog water compared to rain water.

Ion	$F_{\text{this study}}$	$F_{\text{Puerto Rico}}$	$P_{\text{this study}}$	$P_{\text{Puerto Rico}}$	$\approx F/P_{\text{this study}}$
H^+	16.44	15.70	11.03	5.08	1
SO_4^{2-}	125.06	96.45	34.90	23.89	4
NO_3^-	0.39	40.62	0.54	7.47	1
NH_4^+	51.33	23.13	17.07	9.04	7
Cl^-	209.61	397.93	53.42	96.43	4
Na^+	203.33	334.92	51.05	81.30	4
K^+	14.55	10.22	4.69	5.65	3
Ca^{2+}	23.70	64.89	10.30	9.59	2
Mg^{2+}	47.78	66.90	10.76	11.37	4
pH	5.07	5.43	5.20	5.70	—
Lf	62.42	120.08	16.28	24.29	—

Table 3.4: Comparison of weighted mean concentrations of major ions, and pH of fog between this study and studies on the Lägeren (Switzerland), Mount Rigi (Switzerland), Waldstein (E-Germany) and Mont Tremblant (southern Québec).

	NO_3^-	SO_4^{2-}	NH_4^+	pH
Santa Elena Cloud Forest (**this study**)	0.39	125.06	51.33	5.07
Lägeren (Burkard et al. 2003)	623	338	738	4.6
Mount Rigi, Switzerland (Collett et al. 1993)	520	430	1100	5.2
Waldstein, SW-Germany (Thalmann et al. 2002)	646	438	926	4.1
Mont Tremblant, Québec (Schemenauer et al. 1995)[a]	170	339	239	3.7

[a] unweighted means.

3.5 Deposition of Nutrients

The following calculations are based on uncorrected rainfall amounts – which are lower than the 'real' water input due to rain – and have to be used with caution. The additional input of nutrients by fog is of great importance and we therefore focus on the nitrogen and sulphur deposition. The deposition of other chemical elements is disregarded due to the minimal anthropogenic influence on deposition processes. The fog water ionic concentrations and its deposition are mainly determined by the cloud microphysical characteristics and not by emissions due to human activity. The contribution of occult deposition to total input (wet + occult) of NH_4^+-N is quite significant (additional input by occult deposition 51%, based on wet-only deposition as 100%).

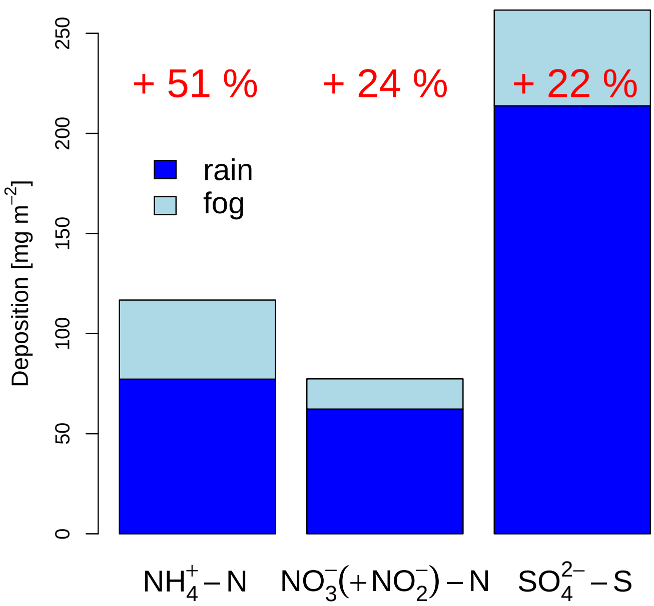


Figure 3.5: Wet and occult reduced/oxidized nitrogen and sulphur input between 20 Februar 2003 and 15 March 2003. The percentages are based on wet-only deposition as 100%.

Chapter 4

Conclusions

Hydrological measurements including sampling of rainfall, throughfall and stemflow were performed in Costa Rica. Interception loss was estimated using the wet variant of the Penman-Monteith equation. Turbulent fluxes of liquid water (cloud water) were measured directly with the eddy covariance method. In order to address the question of the importance of the fogwater input in the hydrological budget of a Costa Rican forest ecosystem, calculations of the water balance were performed, which revealed that the rainfall measurements had to be corrected for wind-induced loss. Under the prevailing meteorological conditions at our field site, rain fell at considerable angle for most of the time. Because of its aspect and inclination, the forest canopy received more rainfall than measured by the rain gauges with horizontal orifices. After the application of the modell by Sharon (1980) for a 65-days lasting period, the corrected rainfall amount was 25.5% higher (510 mm). During the same period, fogwater input (turbulent and gravitational input) was measured to be 16.61 mm, which is only 3.2% of the total water input (rainfall and fogwater) input to the investigated cloud forest ecosystem. This extremely small fraction is in contrast to indirect estimates quantifying this input as 28% of concurrent precipitation input! The calculation of the water balance based on the corrected rainfall data for the entire period showed good agreement. On a daily basis the closure of the water balance was not possible during several days. This discrepancy can be possibly related to effects of footprint mismatches, since troughfall and stemflow were not – even though in the same catchemt – measured on the same slope (different exposition to wind-driven rain). Such uncertainties could be avoided when the hydrological measurements are made within the same footprint area of the tower site. Further analysis on the error bounds of the involved measurements could improve this attempt of the water balance closure.

The ionic concentrations in precipitation and fogwater underline that our field site shows remote site characteristics. Further, the deposition of fogwater is responsible for 22% up to 51% of nutrient (reduced/oxidized nitrogen and sulphur) input compared to the input by wet deposition (rain) to the cloud forest ecosystem.

Even though the project "The Role of Cloud and Fog Water Inputs in the Hydrological Budget of a Tropical Cloud Forest Ecosystem in Costa Rica" funded by the Swiss National

Science Foundation (grant 2100-068051.02) is officially finished, further data analysis will be performed. The next few steps will be

- the re-calculation of the deposition of nutrients (Section 3.5) on the basis of the corrected rainfall amounts;
- the analysis of the error bounds of the measurements included in the water balance closure;
- In the frame of her master thesis Ms. Simone Schmid will further investigate the water balance by analyzing the isotopic signature of the water samples in order to apply the so called 'isotope mass balance' technique, which was successfully applied by Dawson (1998) in order to quantify the contribution of fogwater to a redwood forest in California;
- analysis of additional chemical water samples (not described in this report) which were taken in the surroundings of our field site;
- analysis of the relation between the chemical compounds found in the water samples with the volcanic activity of Mt. Arenal.
- process of the data in order to incorporate them in the database of the research programm 'FIESTA'.

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